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PUMICE PARTICLE BRIDGING AND NUTRIENT LEVELS AFFECT LODGEPOLE AND PONDEROSA PINE SEEDLING DEVELOPMENT

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ABSTRACT

This was a study to determine if both physical and chemical characteristics of the C1 horizon of the Lapine soil, an Entisol developed on Mazama pumice, limit seedling development. Ponderosa and lodgepole pine seedlings were grown in boxes containing successive layers of soil material from the Lapine A1, AC, C1, and C2 horizons. Bulk density of the C1 horizon was varied by packing, and in half the boxes the C1 chemical composition was changed by nutrient additions. Increased bulk densities reduced rooting depths of both species. Nutrient additions decreased root depth of ponderosa pine but increased root and top weight. Nutrient additions did not significantly affect lodgepole pine size. Results indicate that physical properties of the C1 horizon limit root proliferation. The low bulk density values (0.38 to 0.62 g./cm.^{3}), the high percentage of air-filled pore space (above 20 percent), and the nonplasticity of the pumice material indicate that particle bridging and not bulk density per se is the physical factor limiting root penetration.

Keywords: Soil physics, soil chemistry, root development, soil nutrients, soil bulk density, seedlings, ponderosa pine, lodgepole pine.

INTRODUCTION

Dyrness and Youngberg[1/] noted that C1 and C2 horizons of the Lapine soil,[2/] a series developed on Mazama pumice, restrict root development of trees and shrubs. Consequently, roots growing in Lapine soils are often concentrated in two different zones: the weathered portion of the Lapine soil (the A1 and AC horizons) and the upper portion of the older soil profile buried beneath the pumice deposit. Dyrness and Youngberg suggest that the low fertility level of the C horizons may be primarily responsible for the restricted root development. Dyrness[3/] points out, in addition, that the physical characteristics of the C horizons may also be important in limiting root development. Will and Stone,[4/] writing about Taupo pumice soils in New Zealand, state that root expansion in some pumice layers is severely restricted because the rough-surfaced, gravel-sized particles bridge together creating a nonyielding structure.

Auger planting of ponderosa pine (*Pinus ponderosa* Laws.) in pumice soils of central Oregon has been effective in recent years, possibly because the auger mixes weathered and unweathered soil material and breaks up the particle bridging. Placement of fertilizer within the planting hole results in an increase in root development within and below the auger hole but very little lateral root development out into the undisturbed C1 horizon.[5/]

Samples taken at a limited number of field locations in south-central Oregon indicate that the bulk density of the coarse Lapine C1 horizon probably varies between 0.4 and 0.6 grams per cubic centimeter (g./cm.^{3}). The fertility of this horizon is low, a fact particularly evident when the nutrient values are expressed in pounds per acre. Total nitrogen is generally below 0.01 percent by weight and the available phosphorus content as determined by the sodium

[1/] C. T. Dyrness and C. T. Youngberg. Soil-vegetation relationships in the central Oregon pumice region. Proc. 1st N. Amer. Forest Soils Conf., Mich. State Univ., East Lansing, p. 57-66, 1958.

[2/] The Lapine soil is an Entisol having a very dark gray brown (10 YR 3/2 moist) loamy coarse sand or coarse sandy loam A1 horizon approximately 2 inches thick; a yellowish brown (10 YR 5/6 moist) gravelly loam coarse sand AC horizon, 6 to 14 inches thick; a light yellowish brown (10 YR 6/4 moist) medium and coarse pumice gravel C1 horizon, 8 to 20 inches thick, and a light gray (10 YR 7/2 moist) coarse pumice sand and fine pumice gravel C2 horizon, about 14 to 50 inches thick, underlain by the buried soil.

[3/] C. T. Dyrness. Soil-vegetation relationships within the ponderosa pine type in the central Oregon pumice region. Unpublished Ph. D. thesis, Oreg. State Univ., Corvallis, 271 p., 1960.

[4/] G. M. Will and E. L. Stone. Pumice soils as a medium for tree growth. I. Moisture storage capacity. N. Z. J. Forest. 12: 189-199, 1967.

[5/] J. W. Barrett and C. T. Youngberg. Fertilizing planted ponderosa pine on pumice soils. *In* Symp. Ponderosa Pine Regeneration Proc. 1969: 82-88, illus. Oreg. State Univ. Press, Corvallis, 1970.

bicarbonate method is less than 2 parts per million (p.p.m.).[6] Approximately 25 to 37 percent by weight of the C1 horizon consists of gravel-sized particles (greater than 2.0 millimeters), and these particles are bridged together to form a semirigid structure.

Hermann[7] found that ponderosa pine saplings increased growth rates when their roots penetrated the C horizons into the buried soil. He observed that root growth was hindered by the pumice material. He suggested four possible reasons: (1) abrasion of roots caused by movement of the trees due to wind action, (2) mechanical obstruction due to particle bridging, (3) differences in nutrient availability between the pumice layers and the buried profile, and (4) increased availability of water in the buried profile over water in the pumice layers.

The availability of pumice soil water is perplexing. The highly porous C horizons contain water which is held at very low tensions and therefore is available from an energy standpoint. However, poor root proliferation may result in little of this water being available from a positional standpoint. Slow unsaturated flow rates and poor contact between the nonplastic pumice and the root surface may also impede water flow to the root surface.[8] Tigner[9] used a pressure bomb to measure relative water tensions in xylem of mature lodgepole pine growing on Lapine soils with very deep C horizons. In contrast to the above hypothesis, he found that the maximum xylem water stress was never unusually severe even after 2 rainless months and that considerable overnight recovery from stress was maintained. In some of Tigner's study areas, the total depth of the surface A1 plus AC horizons was less than 8 inches and lodgepole roots did not appear to penetrate through the C horizons. If water in the C horizons was relatively unavailable, it is difficult to understand how these trees avoided extremely severe moisture stress.

This study was conducted in a greenhouse to answer the following questions: (1) Do nutrient additions to the C1 horizon increase rooting depths, root weights, and the top weights of lodgepole and ponderosa pine seedlings? (2) Does bulk

[6] Assuming a C1 horizon thickness of 16 inches and a bulk density of 0.5 g./cm.^{3} these values are equivalent to 181 lb./acre of total nitrogen and 3.6 lb./acre of available phosphorus within the C1 horizon.

[7] Richard K. Hermann and Roger G. Petersen. Root development and height increment of ponderosa pines in pumice soils of central Oregon. Forest Sci. 15: 226-237, illus., 1969.

[8] P. H. Cochran. Heat and moisture transfer in a pumice soil. Unpublished Ph. D. thesis, Oreg. State Univ., Corvallis, 165 p., 1966.

[9] Timothy Cary Tigner. Resistance to a needle miner in lodgepole pine. Unpublished Ph. D. thesis, Univ. Mich., Ann Arbor, 79 p., 1970.

density of the C1 horizon influence root penetration and seedling weights? (3) Do small ponderosa and lodgepole pine seedlings respond similarly to changes in C1 horizon nutrient levels and bulk densities? Because field conditions are vastly different, extrapolation of results of this study directly to the field is hazardous.

MATERIALS AND METHODS

Soil materials were placed in 12- by 12- by 18-inch boxes, in layers to duplicate the horizon arrangement of the Lapine profile: 4 inches of C2 horizon material followed by 6 inches of C1, 4 inches of AC, and 2 inches of A1 material for a total soil depth of 16 inches. These soil materials were taken from a pit in the northeast quarter of sec. 1, T. 28 S., R. 10 E., Klamath County, Oregon. A partial physical and chemical analysis of soil from this pit taken from Chichester[10/] is given in table 1. All of the horizons except the C1 were packed to approximately field bulk density.[11/] In six boxes, the C1 material was very lightly packed into the boxes resulting in bulk densities of 0.38 to 0.42 g./cm.^{3}. In six other boxes, the C1 material was solidly packed, resulting in bulk densities ranging from 0.51 to 0.62 g./cm.^{3}.

In three of the boxes from each bulk density range, the C1 horizon was fertilized by thoroughly mixing 600 p.p.m. elemental nitrogen, 300 p.p.m. elemental phosphorus, and 90 p.p.m. elemental sulfur[12/] with the soil before packing. These nutrient levels were estimated to be necessary for maximum top growth by extrapolating response surfaces published by Youngberg and Dyrness.[13/] Commercial ammonium nitrate (34-0-0), treble super phosphate (0-45-0), and gypsum (16.7-percent S) were used as nutrient sources.

To summarize, there were four C1 horizon treatments replicated three times:

(1) Nonfertilized, bulk density 0.51 to 0.57 g./cm.^{3}
(2) Nonfertilized, bulk density 0.38 to 0.42 g./cm.^{3}
(3) Fertilized, bulk density 0.54 to 0.62 g./cm.^{3}
(4) Fertilized, bulk density 0.40 to 0.41 g./cm.^{3} .

10/ F. W. Chichester. Clay mineralogy and related chemical properties formed on Mazama pumice. Unpublished Ph. D. thesis, Oreg. State Univ., Corvallis, 165 p., 1967.

11/ Core sampling in the area resulted in field bulk densities of 0.71, 0.76, 0.44, and 0.53 g./cm.^{3} for the A1, AC, C1, and C2 horizons, respectively.

12/ Using the C1 horizon thickness shown in table 1, and a field bulk density of 0.44 g./cm.^{3}, these nutrient additions are equivalent to field additions of 1,016 lb./acre N, 508 lb./acre P, and 152 lb./acre S.

13/ C. T. Youngberg and C. T. Dyrness. Biological assay of pumice soil fertility. Soil Sci. Soc. Amer. Proc. 29: 182-187, illus., 1965.

Table 1.--*A partial chemical and physical analysis of the Lapine soil used in this study*[1/]

Horizon	Depth	Available P	Total N	Organic matter	>2.0 mm. gravel
	Inches	*Parts per million*	- - - *Percent*	- - -	*Percent by weight*
A1	0-2	20.5	0.086	6.97	14.39
AC	2-11	4.5	.041	1.88	16.39
C1	11-28	1.0	.008	.99	33.39
C2	28-53	1.0	.003	.10	25.95

[1/] These values were taken from more complete analyses given by F. W. Chichester. Clay minerology and related chemical properties of soils formed on Mazama pumice. Unpublished Ph. D. thesis, Oreg. State Univ., Corvallis. 165 p., 1967.

In each box, eight 1-week-old ponderosa pine seedlings were transplanted alternately with eight 1-week-old lodgepole seedlings at a 2- by 2-inch spacing. The seedlings were grown for 120 days, which allowed the majority to set buds, in a greenhouse under a 15-hour photo period. The average day and night temperatures in the greenhouse were approximately 78° and 65° F.

While the seedlings were growing, the soil was watered to maintain the water content found in the field in early spring. These water contents are approximately 45 percent by weight for the A1 and AC horizons, 90 percent by weight for the C1 horizon, and 60 percent by weight for the C2 horizon. Calculation of the air-filled pore spaces from the bulk densities and the particle density of 2.61 g./cm.^{3} shows that even at a C1 bulk density of 0.62 g./cm.^{3} and a water content of 90 percent by weight, the air-filled pore space is above 20 percent.

During the experiment, no mortality occurred in the high bulk density treatments and only two plants died in the low bulk density treatments. Both were lodgepole pine.

When the experiment was terminated, the side of each box was removed and each plant carefully excavated. Rooting depth, dry weights of tops, and roots and top-root ratios were determined. Plant parts were dried at 90° C. for 2 days before weighing.

STATISTICAL ANALYSIS

Although bulk density is the measured soil physical property in this study, particle bridging is the variable which probably affects root penetration. No measurements of particle bridging are available for pumice soils, and therefore the relationship between particle bridging and bulk density for any given particle size distribution is unknown. As roots penetrate through the C1 horizon, they must either pass through the pore spaces between particles or through the individual particles. If bulk density of C1 material is increased without changing the particle size distribution, the pore space between particles is reduced. When the roots become larger than the pore spaces, the particles must be moved or rearranged and at times, broken. Particle bridging opposes rearrangement and movement of the particles; therefore bridging becomes more limiting at the high bulk densities.

At the start of the experiment, the boxes were randomly placed on a greenhouse bench. The design is a completely randomized split plot with three replications. In addition to the split plot analysis of variance, separate analyses of variance were carried out for each species using a completely random design. Analyses of variance for each species were performed to separate the effects of averaging the two species in the split-plot analysis. Inferences drawn from the separate analyses about individual species are conditioned on the fact that both species were grown together.

RESULTS

Although lateral roots were not counted and measured, it was obvious that the lateral root volume for both species was concentrated in the A1 and AC horizons on all treatments. All ponderosa pine seedlings had taproots which penetrated into, and in some treatments through, the C1 horizon. The lodgepole pine tended to have a taproot system which branched more than the ponderosa root system but penetrated at least into the upper portion of the C1 horizon (table 2).

Additions of nutrients to the C1 horizon decreased the root depth of ponderosa pine but increased the root, top, and total dry weights of this species (tables 2 and 3). Top-root ratios of ponderosa pine tended to be increased by nutrient additions, but this increase was not significant. Nutrient addition alone did not significantly affect root depth, top-root ratios, or the root, top, and total dry weight of lodgepole pine. However, lodgepole pine top weights and ratios of top to root tended to be larger for the fertilized treatments. High bulk densities reduced root depths of both species but did not significantly affect root, top, and total dry weights of either species.

Table 2.--*Average ponderosa and lodgepole pine rooting depths, root weights, top weights, top-root ratios, and total weights for high and low C1 bulk densities with and without nutrient additions*

Treatment		Ponderosa pine					Lodgepole pine				
C1 bulk density	Fertilized?	Rooting depth	Root weight	Top weight	Top-root ratio	Total weight	Rooting depth	Root weight	Top weight	Top-root ratio	Total weight
		Inches	- - *Grams*	- -		*Grams*	*Inches*	- - *Grams*	- -		*Grams*
0.62	Yes	10.2	0.19	0.36	1.90	0.54	7.0	0.07	0.21	3.00	0.28
.59	Yes	8.8	.40	.71	1.78	1.11	7.6	.10	.24	2.40	.34
.54	Yes	11.5	.31	.73	2.36	1.04	7.0	.08	.25	3.12	.33
Average		10.1	.30	.60	2.01	.90	7.2	.08	.23	2.84	.32
.57	No	11.8	.13	.18	1.38	.31	6.9	.03	.08	2.67	.11
.52	No	12.8	.12	.11	.92	.23	6.6	.04	.04	1.00	.08
.51	No	13.0	.20	.35	1.75	.55	7.6	.08	.21	2.63	.29
Average		12.5	.15	.21	1.35	.36	7.0	.05	.11	2.10	.16
.41	Yes	13.3	.21	.41	1.95	.62	8.0	.07	.13	1.86	.20
.40	Yes	13.1	.49	.69	1.41	1.18	9.0	.12	.24	2.00	.36
.40	Yes	12.8	.23	.55	2.39	.78	9.6	.06	.17	2.83	.22
Average		13.1	.31	.55	1.92	.86	8.9	.08	.18	2.23	.26
.42	No	15.5	.13	.18	1.38	.31	8.3	.05	.09	1.80	.14
.41	No	15.4	.21	.35	1.67	.56	12.1	.13	.21	1.62	.33
.38	No	15.4	.19	.42	2.21	.61	10.9	.11	.20	1.82	.31
Average		15.4	.18	.32	1.75	.49	10.4	.10	.17	1.74	.26

Table 3.--*F values for the analyses of variance carried out for each species*

Variable	Ponderosa pine			Lodgepole pine		
	Fertility level	Bulk density	Bulk density x fertilizer	Fertility level	Bulk density	Bulk density x fertilizer
Rooting depth	29.15**	43.78**	0	1.22	16.01**	2.97
Root weight	6.15*	.10	.02	.32	1.84	1.73
Top weight	12.16**	.10	.69	3.34	0	2.25
Top-root ratios	2.99	.41	1.09	3.34	2.07	.15
Total weight	10.39*	.11	.37	2.04	.16	2.04

*Significant at the 95-percent confidence level.
**Significant at the 99-percent confidence level.

Table 4.--*F values for split plot analysis of the measured plant variables*

Variable	F values for split plot analysis						
	Fertility level	Bulk density	Interaction (fertilizer bulk density)	Species	Species x fertility	Species x bulk density	Species x fertility x bulk density
Rooting depth	19.02**	59.71**	1.52	112.90**	3.05	0.19	2.05
Root weight	4.43	.33	.20	50.43**	8.92*	.03	.34
Top weight	10.08*	.06	1.24	61.01**	14.64**	.24	.03
Top-root ratios	3.79	.39	.52	14.52**	.64	6.60*	.24
Total weight	9.58*	.16	.90	43.04**	9.10*	.04	0

*Significant at the 95-percent confidence level.
**Significant at the 99-percent confidence level.

Ponderosa pine seedlings rooted deeper than lodgepole pine and had larger tops and roots, but smaller top-root ratios (tables 2 and 4). This difference in size is not surprising since ponderosa pine seed is about 11 times heavier than lodgepole pine seed and the dry weights of week-old ponderosa seedlings are approximately four times that of week-old lodgepole seedlings. Fertilizer addition tended to reduce the root depths of ponderosa pine more than lodgepole pine, but this difference was not significant. There were differences between species in response of top-root ratios to increasing bulk densities. The average top-root ratio for lodgepole increased with increasing bulk density, with and without fertilizer addition. The average top-root ratio of ponderosa pine decreased with increasing bulk density where no fertilizer was added.

DISCUSSION

Nutrient additions increased the weight of ponderosa pine more than lodgepole pine partly because the ponderosa pine roots penetrated deeper into the fertilized layer which started 6 inches below the surface. The larger root systems of the ponderosa pine were probably able to take up greater quantities of added nutrients during the growing period. This difference between species in response to added nutrients is due, at least in part, to greater initial size of the ponderosa seedlings. However, roots of lodgepole pine may be less able than those of ponderosa to physically penetrate the C1 horizon.

The decreased rooting depth of ponderosa pine with nutrient additions is somewhat surprising. However, Sutton,[14/] in a review of factors controlling the form and development of conifer root systems, cites a number of papers in which high fertility levels were associated with a greater number of roots per soil volume, increased root branchiness, and shorter, stubbier roots than were low soil fertility levels. The greater root weights and decreased rooting depths of ponderosa from the fertilized treatments suggest that the photosynthate manufactured by the larger plants was used to enlarge the root system in the zones where nutrients were readily available. In the low bulk density treatments, ponderosa pine taproots barely penetrated the fertilized C1 horizon; while in the nonfertilized treatments, the majority of ponderosa pine taproots penetrated to the bottom of the box. Observations made during removal of the roots indicated that root enlargement with fertilization took place in the A1, AC, and C1 horizons. However, enlargement of the root system seemed to be greatest in the A1 and AC horizons where particle bridging does not impede root proliferation.

[14/] R. F. Sutton. Form and development of conifer root systems. Tech. Commun. No. 7, Commonwealth Forest. Bur., Oxford, Engl., 131 p., illus., 1969.

The decreased rooting depth found in the greenhouse for ponderosa pine with fertilization does not necessarily mean that root penetration through the unweathered C horizons in the field will be slowed by placing fertilizer in the planting hole. Root penetration through the C horizons in the field can take several years.[15] Fertilization produces a plant with larger initial top and root systems, and the larger roots may penetrate the C horizons more rapidly in the years following plant establishment than the roots of smaller nonfertilized plants. Increased withdrawal of C horizon water by enlarged root systems should give the initially fertilized plant an added advantage in the field where water in the surface layers often approaches or exceeds 15 bars tension in late summer.

CONCLUSIONS

Both physical and nutrient characteristics of the C1 horizon may limit seedling development in the field even when water in all soil horizons is held at very low tensions. The low bulk density values, the high percentage of air-filled pore space, and the nonplasticity of the pumice material indicate that particle bridging is the physical factor limiting root penetration. The physical limitation of root penetration suggests that some comparisons between machine and auger planting should be made in the pumice soil region. Possibly auger planting results in more rapid penetration of roots through the unweathered C horizons into the buried soil profile and hence more rapid juvenile growth.

[15] See footnote 7, page 3.

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